FTUV-05-0929

Bursts of pions as a signature of Quark Gluon Plasma

Vicente Vento

Departamento de Física Teórica and Instituto de Física Corpuscular
Universidad de Valencia - Consejo Superior de Investigaciones Científicas
46100 Burjassot (València), Spain,
Email: Vicente.Vento@uv.es

Abstract

We study the behavior of the scalar glueball inside a Quark Gluon Plasma. We follow the fireball from the plasma phase to the hadronic phase and observe that an interesting phenomenon, bursts of pions describing the flow of matter, occurs which might have experimental consequences as a signature of Quark Gluon Plasma.

Pacs: 14.80.-j, 24.80.+y, 25.75.Nq
Keywords: quark, gluon, glueball, meson, plasma

Quantum Chromodynamics (QCD) is the theory of the strong interactions [1]. At low temperatures its elementary constituents are mesons and glueballs [2], this is the hadronic phase where all states have no color, i.e. they are color singlets. On the contrary, at high temperatures a phase transition, called de-confinement (liberation of color), takes place and its elementary constituents become color quarks and gluons. This phase is known as the Quark Gluon Plasma (QGP)[3]. Our aim is to study the behavior of QCD in the transition from the QGP to the hadronic phase centering our attention in the behavior of the scalar glueballs. These particles are bound states of gluons, the gauge bosons of QCD. This unique structure led to an intense experimental search, since they were first theoretically contemplated [2], which has not produced yet a clear picture of their spectrum . Recently, we have proposed an interpretation of the scalar particles that contemplates a rich low lying glueball spectrum [4]. We describe here a scenario for the transition from Quark Gluon Plasma (QGP) to hadronic matter which arises from the behavior of the lightest glueball, the scalar 0^{++}, as the fireball cools in heavy ion collisions [5]. Our scenario manifests itself experimentally as peculiar bursts of pions describing the matter flow in the fluid created by the two colliding ions.

The realization of scale symmetry in Gluodynamcis (GD), the theory with gluons and no quarks, provides a relation between the parameters of the lightest scalar glueball, hereafter called g, and the gluon condensate [6, 7, 8],

$$m_g^2 f_g^2 = -4 \ < 0| \ \frac{\beta(\alpha_s)}{4\alpha_s} \ G^2 \ |0 >, \tag{1}$$

where $f_g =< 0|g|0 >$, m_g the g mass, and the right hand side arises from the scale anomaly. GD provides a description for glueballs which almost coincides with that of QCD in the limit when the OZI rule is exactly obeyed, i.e., when decays into quarks which require gluons are strictly forbidden. This limit we have called OZI Dynamics (OZID) [4].

Lattice results [9, 10] and model calculations [11, 12, 13] support the traditional scenario [14, 15], that the condensate is basically constant up to the phase transition temperature T_C ($150MeV < T_C < 300MeV$) and decreases slowly thereafter until it dilutes (or evaporates) into gluons at $(2-3)T_C$. In this regime the mass of g changes slowly across the phase transition [11, 12, 13] and might even increase beyond T_C as the gluon binding energy decreases [16]. These results and Eq.(1) determine that f_g will be small only close to the dilution temperature when, in GD, scale invariance is restored. However, around T_C, f_g is sizeable and therefore we are able to use in the scalar sector the OZID approximation of QCD, where glueballs and mesons are almost decoupled, and therefore the scalar glueballs of QCD behave similarly to those of GD [4].

We assume for our discussion a recent formulation of the dynamics in the re-

gion above T_C, which states that despite de-confinement the color Coulomb interaction between the constituents is strong and a large number of binary (even color) bound states, with a specific mass pattern, are formed [16]. With this input, the scenario we envisage for GD goes as follows. The strong Coulomb phase is crowded with gluon bound states and g is the lightest. As we move towards the dilution limit, the binding energy of these states decreases, the gluon mass increases, and therefore the color and singlet bound states increase their mass softly until the gluons are liberated forming a liquid [16, 17, 18]. However, as we cool towards the confining phase, color and singlet states decay into the conventional low lying glueballs, in particular g. The fact which makes this scenario appealing is that the multiplicity of glueball channels grows tremendously above the phase transition. The ratio of glueball to meson channels goes from 1 to 8 below the phase transition to 1 to 2 above. We expect the number of glueballs to be very large in the cooling of the fireball. We are not the first to single out glueballs as a possible signature of QGP [19] but certainly both mechanisms and their consequences are completely diverse.

When two heavy ions collide at ultra-relativistic energies, if the collision is quite central, a hot region of space time is produced called the fireball [5]. Let us incorporate in the cooling of the fireball the dynamics of QCD as described in our scenario. Our starting point is a plasma with a temperature $T_C < T < 3T_C$. This plasma is almost a perfect fluid of hadronic matter with low viscosity and is full of binary states [16]. The lowest mass $q\bar{q}$ states are the pseudoscalar pion π and the scalar meson σ, which are here bound states of the strong color interaction. The lightest glueball state is g. The behavior of g runs together with all other hadronic processes leading to a collective flow but, in the OZID approximation, it can be singled out.

As the fireball cools the large number of gluonic bound states decay by gluon emission into g's. The emitted gluons form new bound states of lower mass, due to the strong color Coulomb interaction. As we approach the confinement region the mass of the color bound states increases and it pays off to make multiparticle color singlet states, which decay by rearrangement into ordinary color singlet states. Since the coupling is strong and the phase space is large, these processes take place rapidly. Thus in no time, close to the phase transition temperature T_C, a large number of scalar glueballs populate the hadronic liquid. In our idealized OZID world they interact among themselves and with quark matter only by multi gluon exchanges, i.e., weak long range color Van der Waals forces. Color factors make the $g - g$ interaction stronger than the $g - q$ ($g - \bar{q}$) one. Thus the former produce droplets of a glueball liquid within a background of hadronic liquid and the weak residual interaction between the glueballs and quark matter makes these g-droplets be dragged by the hadronic liquid with the flow determined by the kinetics of the binary states from which

they all proceed.

The g-droplets have a large mean free path since they interact weakly with quark matter and therefore as the liquid slows down by the increase of the hadronic interactions the g-droplets escape from the liquid flowing transversally faster, at which point they start to encounter other droplets and percolate into larger and larger droplets. Thus we arrive to a geometry of g-droplets following the flow of hadronic matter.

The scalar glueball g decays into pions by mixing with a scalar σ meson [4]. If we assume that the σ is the O(4) partner of the π in the chiral symmetric realization of QCD, its mass starts to decrease before the phase transition, becoming degenerate with the pion . Moreover, since in the strong Coulomb phase chiral symmetry is restored, it remains degenerate thereafter [16] (see Fig.1). The mass of g does not vary in this region appreciably. Thus even before we reach T_C the mixing between g and σ disappears because their masses become very different (see Fig.1) . Therefore g becomes stable. This stability remains in the strong color Coulomb phase, since when the mass of the σ increases to the point of allowing mixing, its degeneracy with the pion does not allow for the 2π decay process (see Fig.1) .

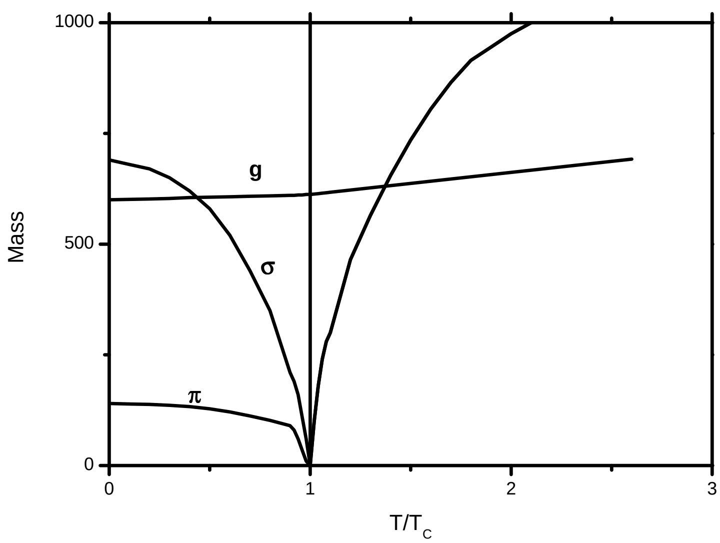

Figure 1: Schematic representation of the behavior of the masses of σ,π and g across the QGP phase transition.

Now we have all the ingredients to discuss the observational signatures of our scenario. From the previous discussion it is clear that the g-droplets are stable in the strong color Coulomb phase. As the fireball cools, the g's cross the phase

transition point as stable states and only when the value of the σ mass increases close to that of the g ($T < T_C/2$), certainly higher than $2m_\pi$, decay may take place (see Fig.1). This mechanism provides us with a "long time span" after the phase transition. Thereafter mixing occurs, however in the approximation of ref.[4], $\Gamma_g << \Gamma_\sigma \sim 100$ MeV, since the latter is a typical hadronic width. Thus the g-droplets "live much longer" than the conventional hadronic states and therefore they are the last states to decay. Moreover, since the g-states have been formed in a determined geometry, namely droplets following the elliptic flow, we expect almost simultaneous bursts of pions arising from the droplets covering the topology of the detector and describing the behavior of the flow. If the g-droplets condense coherence would lead to more spectacular bursts.

Thus our observational signature of glueballs in QGP is a distribution of pionic bursts following the ellipsoidal flow arising from droplets, which happen after all other pionic emissions have taken place. Since the droplets, up to the point of decay, have been flowing faster than the rest of the hadronic medium the bursts maintain the well defined production geometry.

How to detect this signature does not look easy. If we could make a "movie", by binning the time periods of arrival of pions, the lasts bins would contain the proposed bursts. Moreover, since half of the pions that will come out of the decay are π^0's one could attempt to correlate the pionic bursts with gamma bursts arising from $\pi^0 \rightarrow 2\gamma$.

Let us conclude by stating that we have analyzed the behavior of a peculiar hadronic state, the scalar glueball, in a hot hadronic medium. We have discussed in physical terms how these particles, which are created copiously in the strong color Coulomb regime, behave as the fireball cools down. We have seen that their weak coupling with other hadronic states provide them with a well defined behavior in the plasma as the temperature drops. This behavior is transferred to its detectable decay products leading to a peculiar emission of pions (and photons) in the forms of bursts of particles, which hints a possible signature for QGP formation. Our most important result is, that the stability of the glueball across the phase transition up to the point where mixing with the sigma occurs, together with the subsequent small decay width into pions confer to the realization of our proposed observation plausibility.

Acknowledgments

I would like to thank K. Langfeld and B.-J. Schaefer for clarifying information regarding their work. I acknowledge the hospitality extended to me by the GSI theory group, were this research was initiated, and in particular the conversations with Bengt Friman were illuminating.

References

[1] H. Fritzsch, M. Gell-Mann and H. Leutwyler, Phys. Lett. B47 (1973) 365.

[2] H. Fritzsch and P. Minkowski, Nuov. Cim. 30A (1975) 393.

[3] E.V. Shuryak, Phys. Rep. **61** (1980) 71.

[4] V. Vento, "The scalar glueball spectrum", hep-ph/0401218.

[5] Nucl. Phys. A 757 (2005) 1- 283, *First three years of operation of RHIC.*

[6] J. Schechter, Phys. Rev. D21 (1980) 3393.

[7] A.A. Migdal and M.A. Shifman, Phys. Lett. 114B (1982) 445.

[8] J. Lanik, Phys. Lett. 144B (1984) 439; J. Ellis and J. Lanik, Phys. Lett. 150B (1985) 289.

[9] T. Kodama, Brazilian Journal of Physics **34** (2004) 205; P. Petreczky hep-lat/0409139; F. Karsch hep-lat/0106019.

[10] K. Lanfeld et al., hep-lat/0110024.

[11] J. Sollfrank and U. Heinz, Z. Phys. **C65** (1995) 111.

[12] A. Drago, M. Gibilisco and C. Ratti, Nucl. Phys. **A742** (2004) 165.

[13] B.-J. Schaefer, O. Bohr and J. Wambach, Phys. Rev. **D65** (2002) 105008.

[14] H. Leutwyler, "Deconfinemente and Chiral symmetry" in QCD 20 Years later, P.M. Zerwas and H.A. Castrup (Eds.) (World Scientific, Singapore 1993).

[15] D.E. Miller, Acta Physica Polonica **B28** (1997) 2937 and hep-ph/9807304.

[16] E. Shuryak and I. Zahed, Phys. Rev.**D69** (2004) 046005; E.V. Shuryak and I. Zahed Phys. Rev. **C70** (2004) 021901(R).

[17] A.M. Polyakov, Phys. Lett. **B82** (1979) 2410.

[18] A. Linde, Phys. Lett. **B96** (1980) 289.

[19] E. V. Shuryak, Phys. Lett. **B515** (2001) 359.